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Measurement of the $t\bar{t}$ Production Cross Section in Vertex-Tagged Lepton+Jets Events

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We present an updated measurement of the $p\bar{p} \rightarrow t\bar{t}$ production cross section at $\sqrt{s} = 1.96$ TeV in the lepton + jets channel using data corresponding to 695 pb^{-1} of integrated luminosity. We require at least one secondary vertex (SECVTX) tag in the events with $H_T > 200$ GeV and at least 3 tight jets. In this sample, we measure a cross section of $8.2 \pm 0.6(\text{stat.}) \pm 1.0(\text{syst.})$ pb.

Preliminary Results for Winter 2006 Conferences

I. INTRODUCTION

At the Tevatron, protons and antiprotons collide at a center-of-mass energy of 1.96 TeV. The $t\bar{t}$ pair production cross section at such energies is a basic measurement which offers insight into top quark physics in the context of QCD. Theoretical calculations predict a $t\bar{t}$ production cross section of $6.7^{+0.9}_{-0.7}$ pb^{-1} [1] for a top quark mass of 175 GeV/c^2. A significant deviation from the predicted value would be an indication of new physics in either the top quark production or decay.

Previous results for the $t\bar{t}$ cross section in the b-tagged lepton + jets sample corresponding to $320\,\mathrm{pb}^{-1}$ were somewhat limited by statistical errors [3, 4]. We reduce greatly that error by using similar techniques on a sample with more than double the integrated luminosity.

II. DATA SAMPLE & EVENT SELECTION

This measurement uses current high-E_T lepton data samples comprising an integrated luminosity of $695\,\mathrm{pb}^{-1}$, collected between March 2002 and September 2005. The data are collected with the inclusive high-E_T electron and muon triggers, which select leptons above 18 GeV in the central part of the CDF detector. The CDF detector is described in Ref. [2].

Events are required to have an isolated electron or muon with $E_T(p_T) > 20$ GeV and $\not\!\!E_T > 20$ GeV. Jets reconstructed with a cone of central angle 0.4 are counted only if $E_T > 15\,\mathrm{GeV}$ and $|\eta| < 2$. The $t\bar{t}$ signal significance of the selection can be enhanced by requiring large total event transverse energy. In particular, we define the quantity H_T as the scalar sum of the transverse energies of all kinematic objects in the events, including all jets with $E_T > 8\,\mathrm{GeV}$ and $|\eta| < 2.4$:

$$H_T = \Sigma_{\mathrm{all\ jets}} E_T + \not\!\!E_T + E_T^{\mathrm{lepton}} \tag{1}$$

and we require the value of H_T be greater than 200 GeV. (This requirement is dropped for the cross check using the double-tagged sample.)

We also require at least one jet have a secondary vertex tag with significant positive decay length.

A. Secondary Vertex Tagging Algorithm

The SecVtx algorithm relies on the displacement of the secondary vertex relative to the primary event vertex to identify B hadron decays [4]. The primary event vertex is reconstructed for every event with a typical precision of 10-20 μm for $t\bar{t}$ events. Secondary vertex tagging operates on a per-jet basis, where only tracks within the jet cone are considered for b-tagging. Displaced tracks in the jet are selected based on the significance of their impact parameters (d_0) with respect to the primary vertex and are used as input to the algorithm. The algorithm uses a two-pass approach to find secondary vertices: a first pass with loose impact parameter requirements, and a second pass with tighter requirements.

Once a secondary vertex is found, the two-dimensional decay length of the secondary vertex L_{2D} is calculated as the projection onto the jet axis, in the plane tranverse to the beam only, of the vector pointing from the primary vertex to the secondary vertex. The sign of L_{2D} is given by the ϕ difference between the jet axis and the secondary vertex vector (positive for $< 90°$, negative for $> 90°$). The secondary vertices corresponding to the decay of b and c hadrons are expected to have large positive L_{2D} while the secondary vertices from a random set of mis-measured tracks are expected to peak around $L_{2D} = 0$. A jet is said to be positively tagged if the significance $L_{2D}/\sigma_{L_{2D}} > 7.5$, and negatively tagged if $L_{2D}/\sigma_{L_{2D}} < -7.5$. Positively tagged jets have a high purity of of heavy flavor jets and are identified as such, while negatively tagged jets are mostly light jets; we use negative tags to estimate the rate of positive mistags.

B. Total $t\bar{t}$ Acceptance

The acceptance is defined as the fraction of produced $t\bar{t}$ events which are actually observed. The total acceptance is calculated from a combination of data and Monte Carlo. The geometric times kinematic acceptance of the basic lepton+jets event selection is measured using the PYTHIA Monte Carlo program [5]. The efficiency for identifying the isolated, high P_T lepton is scaled to the value measured in the data using the unbiased leg in Z-boson decays. The geometric times kinematic acceptance, as a function of the number of identified jets above 15 GeV, is shown in

Table I. The acceptance differs by lepton type: CEM (central electrons), CMUP (muons with pseudo-rapidity range $|\eta| < 0.6$), and CMX (muons with pseudo-rapdity range $0.6 < |\eta| < 1.1$. The efficiency to tag at least one jet in a $t\bar{t}$ event (after the $H_T > 200$ cut) is $60.4 \pm 3.7\%$, averaged over all lepton types.

	CEM	CMUP	CMX
Average Tag Eff (%)	60.4±0.0888±3.72		
Acc. with tag (%)	2.41±0.00749±0.232	1.28±0.00522±0.125	0.589±0.00351±0.0576
Total Acc. (%)	4.28±0.00978±0.412		
Luminosity	695±40.3	695±40.3	654±37.9
Denominator	16.7±0.052±1.88	8.91±0.0363±1.01	3.85±0.023±0.438
Total Denominator	29.5±0.0675±3.31		

TABLE I: Summary table of $t\bar{t}$ acceptance with $H_T \geq 200$ GeV cut.

	CEM	CMUP	CMX
Ave. doubT Eff (%)	15.2±0.059±2.42		
Total doubT Acc. (%)	1.15±0.00371±0.202		
Total doubT Denominator	7.91±0.0257±1.46		

TABLE II: Summary table of acceptance for double-tagged $t\bar{t}$ events, without H_T requirement.

To measure the efficiency for tagging heavy flavor hadrons, we use a control sample of di-jet events in which one of the jets contains a low-p_T electron. This sample is rich in semileptonic decays of bottom and charm hadrons. We measure the efficiency independently in data and simulation, and we find that the ratio of efficiencies (the "b-tagging efficiency scale factor" is $\epsilon_{\rm data}/\epsilon_{\rm MC} = 0.898 \pm 0.075$. This scale factor is applied to the tagging efficiency determined from the PYTHIA simulated events.

III. BACKGROUNDS

The dominant background for this analysis is production of W boson plus multi-jet events. Unfortunately, theoretical predictions of the W+jets cross section suffer from large uncertainties; we thus rely partially on the data for an absolute normalization. These events enter the signal sample when one of the jets is a heavy flavor jet, or when a light quark jet is mistagged as a heavy flavor jet. Mistags are estimated by parameterizing the rate of negative tags in a control sample as a function of relevant jet and event variables (number of tracks in the jet, jet E_T, η and ϕ of the jet, and sum of the E_T for all jets in the event with $E_T > 10$ GeV and $|\eta| < 2.4$). To first order negative tags are representative of positive mistags since mistags are mostly due to symmetric resolution effects; however, the presence of heavy flavor negative tags, long-lived particles, and nuclear interactions with the detector material contribute asymmetrically to the mistags. We find that the negative tag rates must be corrected by a scaling factor 1.37 ± 0.15 in order to match the positive mistag rate. These predicted tagging rates are then applied to our pretag sample. In order to evaluate the background due to W+ heavy flavor, we use ALPGEN+HERWIG Monte Carlo models to estimate the fraction of the inclusive W+jets events which are $Wb\bar{b}$, $Wc\bar{c}$, or Wc, and multiply that fraction by the number of observed W events in the pretag data sample after correcting for QCD and other backgrounds [6, 7]. By using the Monte Carlo only for the fraction of W events with heavy flavor, uncertainties in the MC due to Q^2 scale and NLO contributions are greatly reduced.

The other substantial background in this analysis comes from events without W bosons. These events are typically QCD multi-jet events where one jet has faked a high-P_T lepton, and mismeasured energies produce apparent missing E_T. We measure this "non-W" QCD background by extrapolating the number of tagged events with an isolated lepton and low missing E_T into the signal region of large missing E_T.

Other small backgrounds from a variety of sources are estimated using events generated with Monte Carlo programs and normalized to the Standard Model cross sections. The predictions for all backgrounds as a function of jet multiplicity are summarized in Table IV.

IV. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in this analysis come from Monte Carlo modeling of the geometrical and kinematic acceptance, knowledge of the secondary vertex tagging efficiency, the effect on the acceptance of the uncertainty on the jet energy scale, uncertainties on the background predictions, and the uncertainty on the luminosity.

Monte Carlo modeling of geometrical and kinematic acceptance include effects of PDFs, ISR and FSR, and jet energy scale. These are estimated by comparing different choices for PDFs and varying ISR, FSR and the jet energy scale in the Monte Carlo. Finally, the modeling of the lepton ID efficiency in events with multiple jets is an additional source of systematic uncertainty on the acceptance. We use a data to Monte Carlo scale factor that is taken from inclusive Z data and Monte Carlo which is dominated by events with no jets. A 2% systematic uncertainty on this scale factor is estimated by convoluting the scale factor measured as a function of ΔR between the lepton and the nearest jet with the ΔR distribution of leptons in $\geq$3 jet $t\bar{t}$ events. The effect of the systematic uncertainties on the cross section measurement are summarized in Table III.

Source	Uncertainty (%)
b-tagging	6.5
luminosity	6.0
parton distribution functions	5.8
jet energy scale	3.0
initial/final state radiation	2.6
lepton identification	2.0
Total	11.5

TABLE III: Summary of systematic uncertainties.

V. RESULTS

Table IV shows a summary of the background estimates for each jet bin and the number of observed vertex-tagged events. These estimates include the statistical and systematic uncertainties on the background predictions. We have also corrected for the non-negligible $t\bar{t}$ contribution to the pretag W+jets sample.

Njets	1	2	3	≥ 4
Pretag	68183	10647	846	402
Mistag	286.0 ± 42.3	119.1 ± 17.7	21.0 ± 3.2	6.6 ± 1.0
$Wb\bar{b}$	201.1 ± 62.3	109.0 ± 32.3	13.0 ± 3.5	3.3 ± 0.9
$Wc\bar{c}$	61.5 ± 18.0	40.9 ± 12.5	5.3 ± 1.6	1.5 ± 0.5
Wc	242.1 ± 62.0	50.4 ± 13.3	3.3 ± 0.9	0.4 ± 0.1
Single Top	17.2 ± 1.7	24.1 ± 2.4	2.1 ± 0.2	0.4 ± 0.1
Diboson	13.3 ± 2.2	19.2 ± 3.0	2.6 ± 0.5	1.0 ± 0.2
non-W QCD	99.9 ± 16.4	45.0 ± 7.5	5.8 ± 1.1	4.1 ± 0.8
Total	921.1 ± 113.3	407.8 ± 52.3	53.0 ± 6.3	17.2 ± 1.9
Data	1029	514	156	158

TABLE IV: Number of tagged events and the background summary, after requiring $H_T > 200\,\text{GeV}$ for events with at least 3 jets.

We calculate the $t\bar{t}$ production cross section as follows:

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{\epsilon_{t\bar{t}} \times \int \mathcal{L}dt} \tag{2}$$

where N_{obs} is the number of events with ≥ 3 tight jets that are tagged with at least 1 b-tag, N_{bkg} is the corrected background and $\epsilon_{t\bar{t}}$ is the total acceptance (geometrical times kinematic times tagging efficiency), taken from Tables IV and I For $t\bar{t}$ events in the tagged sample of W+3 or more jets, we find a cross section of $8.2 \pm 0.6 \pm 1.0$ pb, where the first uncertainty is statistical and the second is systematic. This result assumes a top quark mass of $175\,\text{GeV}/c^2$.

We also measure the $t\bar{t}$ production cross section in a sample of W+jets events which have at least two vertex-tagged jets. In this case, the backgrounds are sufficiently low that we make no requirement on the event H_T. The relevant

Jet multiplicity	2 jets	3 jets	≥ 4 jets
Mistags	2.9 ± 0.5	1.7 ± 0.4	1.0 ± 0.5
Wbb	14.8 ± 4.0	4.7 ± 1.2	1.4 ± 0.4
Wcc	2.3 ± 0.8	0.4 ± 0.1	0.2 ± 0.1
Single Top	2.4 ± 0.5	0.1 ± 0.0	0.0 ± 0.0
Diboson	0.9 ± 0.2	0.2 ± 0.1	0.1 ± 0.0
Non-W QCD	1.0 ± 0.2	0.6 ± 0.1	0.2 ± 0.1
Total Pred	24.3 ± 4.8	7.7 ± 1.4	2.9 ± 0.7
Corrected Total	24.2 ± 4.8	7.2 ± 1.3	1.9 ± 0.5
Top(6.7±0.8 pb)	7.3 ± 1.6	20.4 ± 4.5	31.9 ± 7.1
Observed	29	33	46

TABLE V: Prediction for the number of double-tagged events (SecVtx-SecVtx). Corrected total comes from the $t\bar{t}$ cross section measurement where the pretag sample is corrected for the $t\bar{t}$ contribution. The expected number of $t\bar{t}$ events is calculated using the theoretical cross section of 6.7 pb.

double-tagging efficiency for $t\bar{t}$ events is given in Table II, and the predicted background contributions to the sample are summarized in Table V. We measure a cross section of $8.8^{+1.2}_{-1.1}\,(\text{stat.})^{+2.0}_{-1.3}\,(\text{syst.})$ pb in the double-tagged sample..

Figure 1 shows the number of jets in tagged W+jet events together with a histogram representing the components of the background. Figure 2 shows the H_T distribution for all candidates, before the requirement of $H_T > 200$ has been applied. Figure 3 shows the distribution of the $c\tau$ measurement for vertex-tagged jets in the candidate events. Figure 4 shows the number of jets in double-tagged W+jets events.

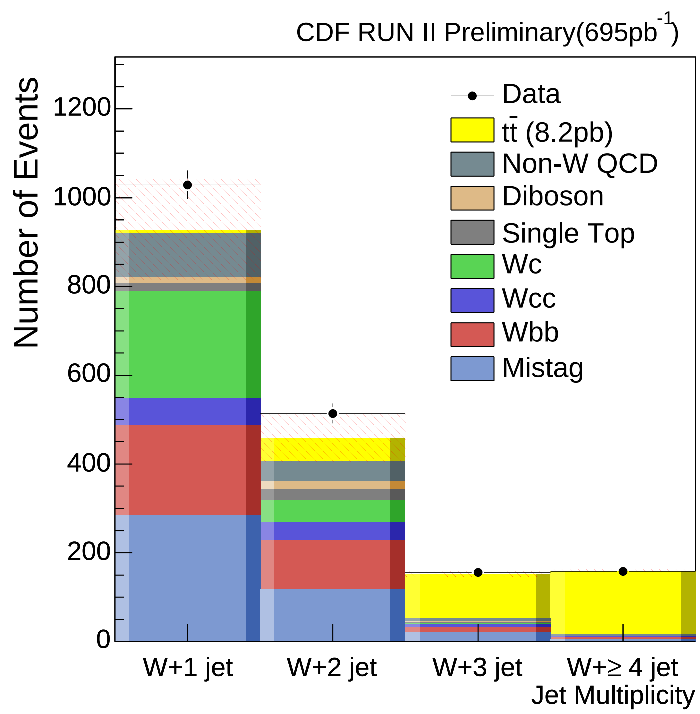

FIG. 1: Observed tagged events as a function of jet multiplicity, after requiring $H_T > 200\,\text{GeV}$ for events with at least 3 jets. The colored histogram represents the background contributions to each bin. (The pretag sample has been corrected for $t\bar{t}$ contribution.)

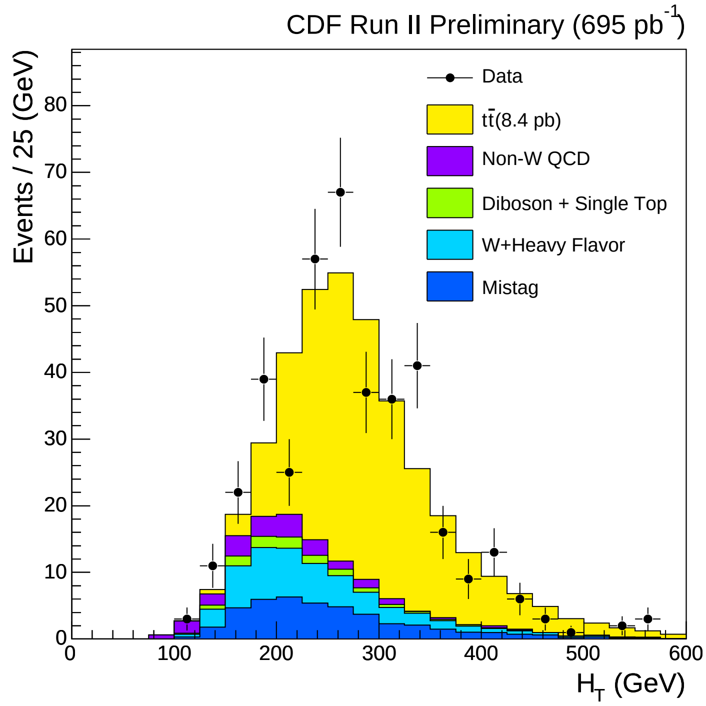

FIG. 2: H_T of candidates before the requirement that $H_T > 200$ GeV.

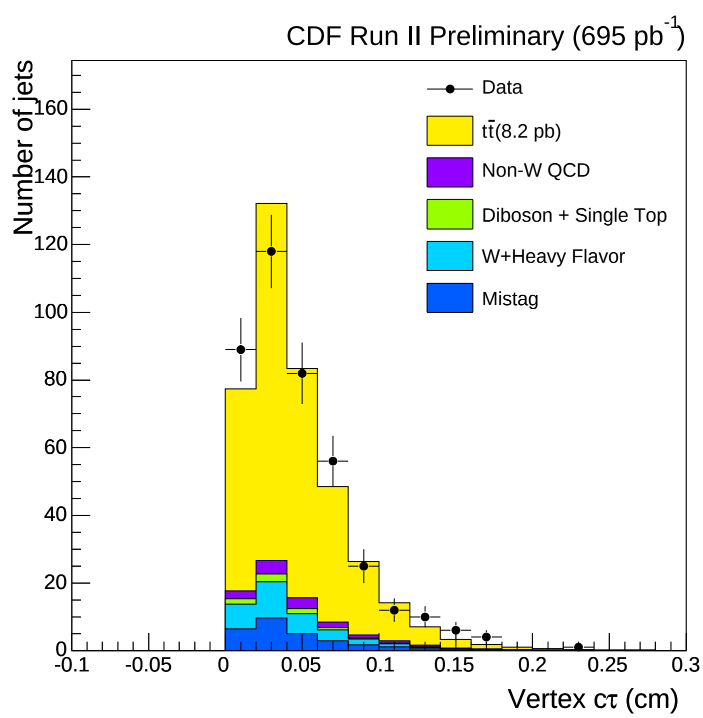

FIG. 3: Distribution of the $c\tau$ measurement for vertex-tagged jets in the candidate events.

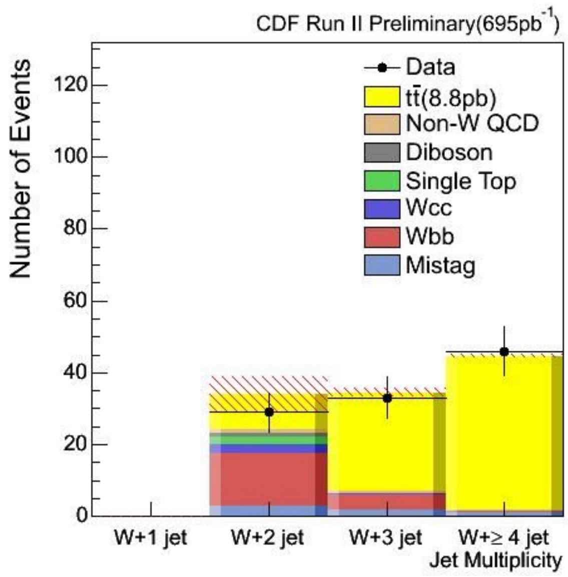

FIG. 4: Observed double-tagged events as a function of jet multiplicity. The colored histogram represents the background contributions to each bin.

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